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ABSTRACT

We provide a theoretical context for understanding the recent work of Kalfountzou et al (2014) showing that star formation is enhanced at lower optical luminosity in radio loud quasars. Our proposal for coupling the assumption of collimated FRII quasar jet-induced star formation with lower accretion optical luminosity, also explains the observed jet power peak in active galaxies at higher redshift compared to the peak in accretion power, doing so in a way that predicts the existence of a family of radio quiet AGN associated with rapidly spinning supermassive black holes at low redshift, as mounting observations suggest. The relevance of this work lies in its promise to explain the observed cosmological evolution of accretion power, jet power, and star formation, in a way that is both compatible with the Soltan argument and resolves the so-called 'Meier Paradox'.

Subject headings: galaxies: active – galaxies: star-formation – galaxies: evolution – galaxies: jets - quasars: supermassive black holes- - X-rays:binaries

1. Introduction

While the black hole scaling relations strongly point to a connection between supermassive black holes and their host galaxies (Kormendy & Richstone 1995; Magorrian et al 1998; Ferrarese & Merritt 2000; Gebhardt et al 2000; Tremaine et al 2002; Marconi & Hunt 2003), our sketchy appreciation of the link between active galactic nuclei (AGN) and star formation suggests that understanding is still lacking depth. Whereas the pure starburst origin to AGN (Terlevich & Melnick 1985; Terlevich et al 1992) is problematic, some observations suggest AGN triggering and star formation are positively correlated (Bongiorno et al 2012; Feltre, et al 2013), while at high luminosities they may (Luts et al 2008; Bonfield et al 2011; Rafferty et al 2011; Juneau et al 2013) or may not (Page et al 2012; Barger et al 2014) be. Disk winds may suppress star formation so the correlation may be negative (Barger et al 2014). In moderate power AGN the possible link between AGN and star formation seems to disappear (Shao et al 2010; Rosario et al 2012; Harrison et al 2012), and models addressing these issues based on the variability timescales in AGN have been proposed (e.g. Hickox et al 2014). There is a need, however, for a global explanation of AGN evolution, which AGN variability does not address, and this needs to be compatible with scale invariance and observations of state transitions in black hole X-ray binaries.

From the Soltan argument (Soltan 1982) we conclude that measured black hole masses and luminosities constrain the accretion history to a non-negligible fraction of the Eddington limit, implying that supermassive black holes have largely been spun up to high values (Fabian & Iwasawa 1999; Elvis, Risaliti & Zamorani, 2002; Wu et al 2013; Trakhtenbrot 2014; Reynolds et al 2014). Observations, therefore, require that we explain high spinning black holes at low redshift associated with radio quiet AGN, in the context of a cosmological evolution experiencing a downsizing of AGN activity constrained such that FRII quasars peak at higher redshift compared to lower average redshift for FRI radio galaxies accreting

hot halo gas and quenching star formation (Cattaneo et al 2009; Merloni et al 2010; Best & Heckman 2012). And while the most powerful FRII quasars peak at about z=2, accretion appears to peak at later times at about z=1 (Barger et al 2001).

Our objective in this paper is to present a phenomenological theoretical framework that has previously been applied to a number of issues in the physics of extragalactic radio sources, to further explore the recent observations of enhanced star formation in radio loud quasars at lower optical luminosity (Kalfountzou et al 2014) in a way that is compatible with the implications of the well known Soltan argument. Our goal is to flesh out and apply a simple idea: Prolonged accretion spins black holes up and turns them into weak jet producers. While that idea is not new, we show for the first time how we can begin an exploration of the AGN-star formation connection within the paradigm in a way that is intimately linked with a contradiction-free understanding of the implications of the Soltan argument. In addition, we also show how the above ideas resolve the so-called 'Meier paradox', referring to a puzzle discovered by astrophysicist David L. Meier in the observed redshift dependence of the radio and optical/X-ray luminosity functions. As we will describe in more detail in the appropriate section, Meier's observation involves a contradiction between the expectation of how the AGN radio luminosity function and the AGN optical/X-ray luminosity function behave as predicted by the standard black hole accretion paradigm and the actual observations of these luminosity functions. Our phenomenological model is based on a prolonged accretion scenario whereby black holes spin up to high prograde values from random initial configurations in which prograde or retrograde accretion is triggered in the aftermath of galaxy mergers, a framework that has already been applied to address the radio loud/radio quiet dichotomy, the FRI/FRII division, the nature of the Fundamental Plane, weak versus strong inner disk reflection features, and the jet-disk connection (Garofalo, Evans & Sambruna 2010, Garofalo 2013a,b; Garofalo, Kim & Christian 2014). In section 2 we describe the basic elements

of our theoretical framework that are needed to interpret the observations. In section 3 we explore the results of Kalfountzou et al (2014) in terms of our model. In section 4 we explore compatibility with the Soltan argument and address the 'Meier Paradox'. In section 5 we juxtapose our semi-analytic framework with recent general relativistic magnetohydrodynamic simulations. In section 6 we summarize and conclude.

2. The Gap Paradigm for black hole accretion and jet formation

2.1. Phenomenological description

The 'gap paradigm' for black holes is a scale-free, phenomenological model for the evolution of accreting black holes (Garofalo, Evans & Sambruna 2010). While retrograde accretion is a fundamental aspect of the model, it is important to note that such modes of accretion apply only to a small subset of the AGN population in the paradigm. Figures 1 and 2 describe the model using a branching tree diagram. In Figure 1 we capture the idea that major mergers in the paradigm are linked to the most massive black holes, which can be either radio loud or radio quiet depending on whether the cold gas forms an accretion disk in retrograde or prograde configurations. In high retrograde spin states, the paradigm prescribes powerful FRII quasars, whereas in high prograde spin regimes the model adopts the jet suppression mechanism (Ponti et al 2012; Neilsen & Lee 2009) implying a radio quiet quasar. For intermediate spins in retrograde configurations in the model, we have less powerful FRII quasars while for intermediate prograde spin we have an FRI quasar. Accretion imposes tight constraints on the evolution of these classes of objects in the sense that the black hole spin evolution toward the prograde regime is not a feature that the model can modify. While accretion enforces a spin-up toward the prograde regime that is independent of model prescription, the character of the accretion flow and the presence or suppression of the jet depends on the ability of the FRII jet to heat the galactic medium.

For the powerful subclass, this is effective, and the radiative efficiency of the disk drops earlier, transitioning the system into an ADAF while still in the retrograde spin regime. In other words, the system has not had enough time to spin down. For the less powerful FRIIs, the radiative efficiency drops later and the system finds itself already in the prograde accreting regime when this occurs, making it an FRI radio galaxy. For a deeper appreciation of the character of this evolution, we refer the reader to section 3.3 of Garofalo, Evans & Sambruna (2010). Eventually the accreting phase ends and a dead quasar remains. For the FRI quasar, prolonged accretion will spin the black hole up further to high spin values which, according to the model, turns the system into a radio quiet quasar where no further evolution into other types of AGN can occur before the system stops feeding and becomes a dead quasar. We emphasize that while transition into radio quiet quasars is possible in the paradigm, transition away from them is not. The reasons for this are twofold: First, a radio quiet quasar is a prograde accreting thin disk in the model, which additional accretion will simply spin further up into the prograde regime, increasing the disk efficiency and jet suppression mechanism, ensuring its radio quiet mode. Two, due to the absence or weakness of the jet, the model prescribes that the state of accretion will remain thin. In short, there are no mechanisms that in the paradigm can push the system out of its radio quiet nature as long as there continues to be sufficient material to accrete. This should be contrasted with the behavior of X-ray binaries that do in fact experience accretion states that transition from soft states into hard states. In other words, feeding from the donor star can produce rather different outcomes for the state of accretion. Therefore, FRII quasar phases are not only short (retrograde accretion can last at most 8 x 10^6 years at the Eddington rate), they also only occur as initial conditions, not later ones in the paradigm. There is, i.e. in the framework, no evolution into an FRII quasar from other active phases. This aspect of the model is crucial in understanding the prediction of different times for the peak in the radio and X-ray/optical luminosity functions vs. redshift explored in the next

section.

At lower redshift the merger function drops (e.g. Bertone & Conselice 2009) and the fraction of retrograde accreting black holes follows suit, giving way to a preponderance of prograde accreting black holes at later times. This is captured in the branching-tree diagram of Figure 1 labelled 'lower redshift', with the size of the boxes capturing the density of such states. The boxes representing the FRII morphologies, in fact, are smaller, while those representing prograde accreting black holes are larger. Cosmic downsizing, thus, has a direct impact on the generation of FRIIs in the paradigm, decreasing both their numbers and those of the objects that are linked to them at lower redshift.

For black holes governed by secular processes, which appear to dominate AGN feedback at least at redshift less than about 1 (e.g. Cisternas et al 2011; Draper & Ballantyne 2012), the AGN branching tree of Figure 2 applies. The crucial difference between Figures 1 and the top part of Figure 2 is the nature of the feeding mechanism, mergers in the former and secular processes in the latter. From the perspective of the gap paradigm, depending on the spin and type of accretion, we have LINERs, Γ-NLS1s and radio quiet AGN. The former are the low mass equivalent of the FRI radio galaxies – albeit in accretion modes that are not as ineffective at launching disk winds as radio mode accretion is - hence their spins can span the entire prograde regime. Γ-NLS1s are modeled as jetted objects in thin disk configurations, which requires that the spin not exceed the threshold value for jet suppression, allowing them to live in some intermediate spin range, making them lower mass black hole analogs of the FRI quasars/AGN, but fed by secular processes thought to dominate dynamics in spiral galaxies. The radio quiet AGN of Figure 2, finally, are simply the lower mass equivalent of the radio quiet, high prograde spinning quasar/AGNs, but fueled by secular processes as opposed to mergers. Again, note how the radio quiet quasars/AGN do not evolve into other AGN states prior to terminating their duty cycle.

Because black hole spin evolution is a main driver of change due to the tight dependence of disk and jet efficiency on spin, in the paradigm, these objects are the slowest to evolve. In fact, independent of the model, spinning black holes up to high prograde values from zero spin at the Eddington limit, requires more than an order of magnitude greater time than the spin-down from high spin in retrograde configurations at the Eddington limit. In addition, once spin reaches the maximum prograde value, no further spin change can occur and the evolution of such a high-spinning prograde object is governed by the even slower evolution related to its black hole mass. Eventually, of course, the system runs out of fuel and a dormant black hole is produced. For our understanding of how the gap paradigm accommodates the Soltan argument, it is crucial that one appreciate how all objects in this framework tend to die as high-spinning black holes.

The time evolution of X-ray binaries, on the other hand, is insensitive to changes in both black hole spin - which are all prograde - as well as to changes in the distribution of the accretion states over time, as captured by the black print and equal sizes of the boxes, respectively. But the crucial point we wish to emphasize is that the different feeding mechanism in X-ray binaries (the donor star) is such that soft states do indeed evolve into hard states, unlike in their AGN counterparts, a fact that in the gap paradigm is directly connected to physics that only appears in the accreting supermassive black holes. These branching-tree diagrams will help illustrate our application of the model to both the Kalfountzou et al (2014) work as well as to the Soltan argument.

2.2. Mathematical description

The gap paradigm combines three independent theoretical constructs into one global phenomenological model. The most fundamental involves the physics of energy extraction from black holes via the Blandford-Znajek effect (Blandford & Znajek, 1977; henceforth

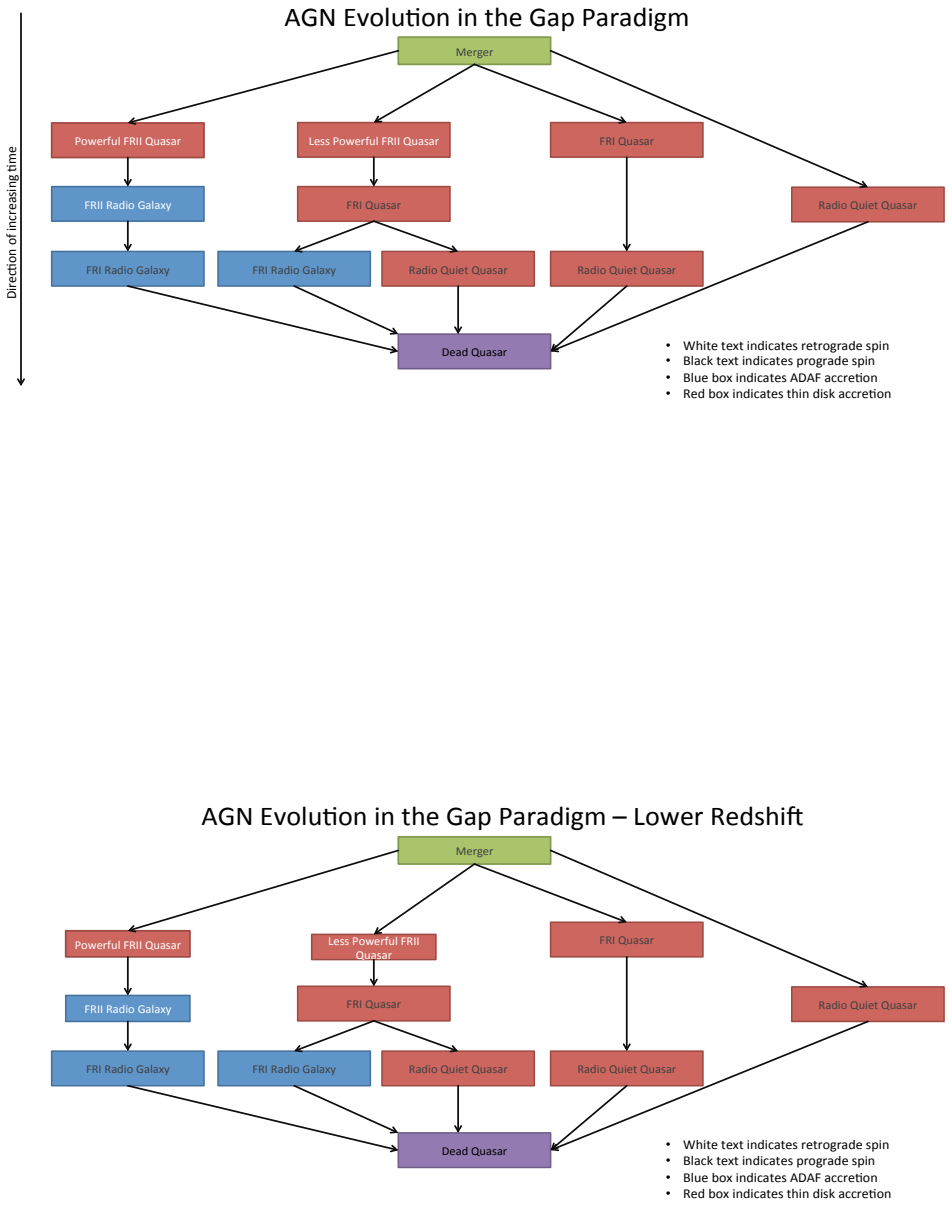
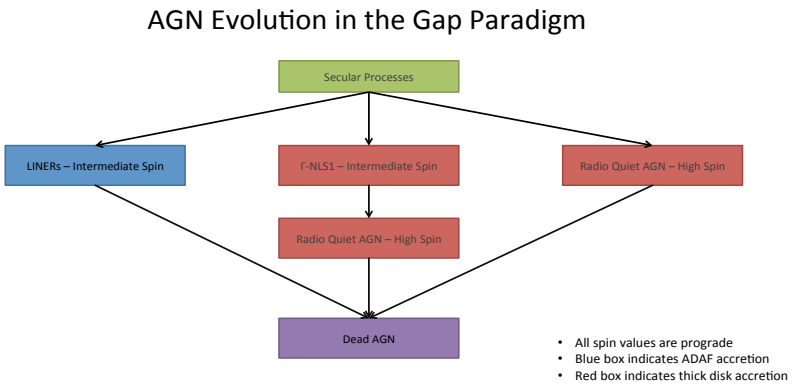


Fig. 1.— On the top is the branching-tree diagram for the time evolution of the most massive black holes formed in major mergers. Two states of accretion characterize the entire population with red representing cold, thin, radiatively efficient accretion, and blue representing radiatively inefficient, ADAF accretion. White labels indicate retrograde, while black labels indicate prograde, accretion. The model predicts radio quiet quasars dominate the density of objects at lower redshift. On the bottom is the branching-tree diagram for the time evolution of AGN at lower redshift at a time when the merger function has dropped so that the number of mergers producing retrograde accreting black holes drops. This is captured in the diagram by the smaller sizes for the boxes representing FRII quasars. The boxes representing prograde objects, accordingly, are larger, capturing the fact that failed retrograde accretion states end up as prograde ones.



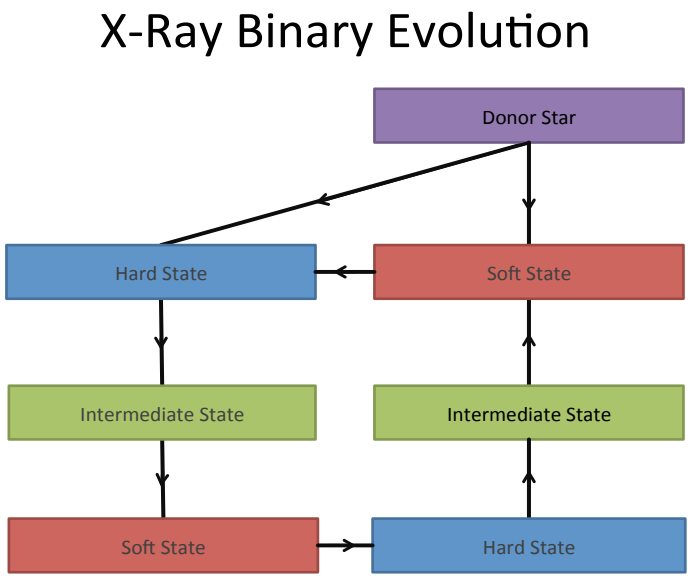


Fig. 2.— On the top is the branching-tree diagram for lower mass black holes that are fed via secular processes. Such lower mass accreting black holes tend to be unstable to retrograde accretion (e.g. Perego et al 2009), effectively ensuring the absence of FRII states. Therefore, all black holes on this diagram are prograde accreting. The other diagram shows the cyclical evolution of X-ray binaries, indicating both an absence of spin evolution (black for prograde) and a cyclical time evolution (the equal sizes of all boxes unlike the AGN case).

BZ), which postulates the relation

$$L \propto a^2 \tag{1}$$

between extracted power and black hole spin parameter a. The other two constructs involve extraction of accretion disk rotational energy via Blandford-Payne jets (Blandford & Payne, 1982) and accretion disk winds (Kuncic & Bicknell, 2004, 2007 as extensions of Shakura & Sunyaev, 1973 and Pringle, 1981). The total outflow power from the Blandford-Znajek effect, the Blandford-Payne mechanism and the Kuncic & Bicknell disk wind is based on the size of the gap region which is imposed on the following standard set of equations. In terms of differential forms, the most concise coordinate-free way of writing Maxwell's equations, the magnetosphere is governed by the standard Maxwell equations with sources, which relate the exterior derivative of the dual Faraday 2-form to the current

$$dF^* = \mu_0 J \tag{2}$$

where

$$F^* = \alpha_{ij} dx_i \Lambda dx_j \tag{3}$$

is the dual Faraday 2-form, μ_0 is the vacuum magnetic permeability, J is the current, α_{ij} constitutes the tensor whose components are differentiable electric and magnetic fields, and the summation convention is implied. In addition, we impose the force-free condition on the Faraday 2-form

$$F \circ J = 0 \tag{4}$$

and finally, we also impose the dissipationless ideal MHD condition

$$F \circ U = 0 \tag{5}$$

where U is the velocity field of the accretion flow. In the accretion disk, instead, the dissipationless condition does not apply and we relate the current to Ohm's law via

$$dF^* = \sigma F \circ U \tag{6}$$

with σ the conductivity, which we treat as constant in both space and time both for simplicity and because it is related to microscopic physics that is not well understood. The extent to which this is a reasonable approximation is beyond our current understanding. By comparison, general relativistic numerical simulations of black hole accretion also impose a constant conductivity everywhere but the value used is infinite. We will discuss this point further in section 5. Since we work directly with the vector potential A, we have

$$F = dA \tag{7}$$

so that F is the exterior derivative of the vector potential, and our equations take the following form.

$$d\wedge dA^* = \mu_0 J \tag{8}$$

$$dA \circ J = 0 \tag{9}$$

and

$$dA \circ U = 0 \tag{10}$$

in the magnetosphere, while the accretion flow is constrained by

$$d\wedge dA^* = \sigma dA \circ U. \tag{11}$$

Stationarity and axisymmetry fully constrain the gauge. We seek solutions of

$$\int \frac{F}{2\pi} = \Psi \tag{12}$$

for a ring constructed using fixed radial and poloidal coordinates in Boyer – Lindquist coordinates. The Ψ function is the invariant magnetic flux function, i.e. the essential coordinate-free quantity whose value determines BZ and Blandford-Payne power (Garofalo, Evans & Sambruna 2010). On top of that we add the power associated with the disk wind, which involves an integral over the entire accretion disk of the local dissipation function. This function can be obtained from Shakura & Sunyaev (1973) to be

$$D(R) = (\frac{3}{8}\pi r^3)GM(\frac{dm}{dt})\Big[1 - (\frac{R_{isco}}{r})^{1/2}\Big] \tag{13}$$

M is the mass of the black hole and dm/dt is the accretion rate. Hence, the wind power at any location r depends on the location of the innermost stable circular orbit, R_{isco}. For locations further out in the disk, the local dissipation from the disk will be greater in the prograde configuration due to the smaller value of R_{isco}. The dependence of D(R) on R_{isco} also ensures that no stress occurs inward of that location and deviations of this have been shown to be of order of a few percent only (e.g. Penna et al 2010). This non-relativistic

calculation is sufficient given that the relativistic correction factors drop off rapidly with r. The bottom line is that jet and disk power depend on the location of R_{isco}, which determines the size of the gap region between the edge of the accreting material and the black hole horizon, i.e. the size of the gap region and the imposed condition of zero magnetic flux threading the gap region (i.e. the 'Reynolds Conjecture' as coined in Garofalo, Evans & Sambruna 2010) constitutes the essential distinguishing feature of our model which we will compare to numerical simulations in section 5. This zero-magnetic-flux assumption in the gap region constitutes a simple yet fundamental difference with respect to the BZ mechanism, which is that the gap is a region where gravity dominates the dynamics. In the accretion disk, instead, gravity and magnetic forces compete while everywhere else the dynamics is magnetically dominated. As described, the equations are solved numerically to obtain the flux function, from which the power in the jet is obtained. The details of this are discussed in the first papers on the gap paradigm (Garofalo 2009a,b; Garofalo, Evans & Sambruna 2010). What concerns us here is the dependence of jet power on the spin of the black hole, which is greater in the high retrograde spin regime (Garofalo 2009a). In the next section we will explore the time evolution of jet power and accretion disk power as a function of time in order to explain recent observations of star formation in AGN.

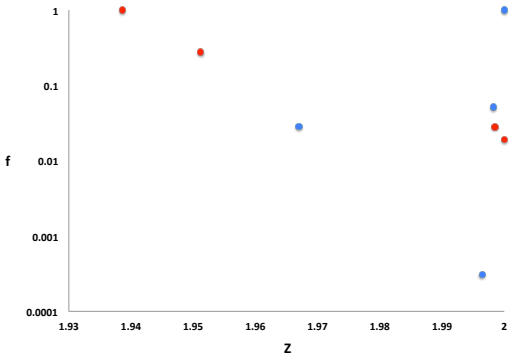
3. AGN-star formation link and peak in jet vs disk power

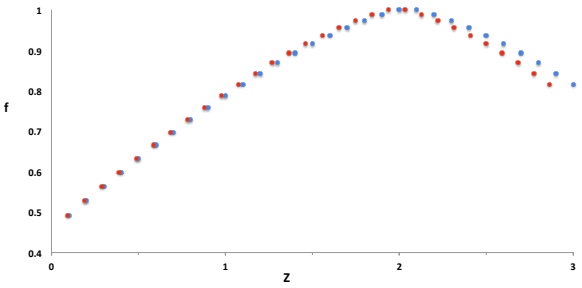
Based on the constraints of our prolonged accretion scenario, we calculate the redshift dependence of the luminosity of jets and accretion according to the prescription of the gap paradigm. If we assume a high retrograde black hole spin as the initial configuration, the time required to spin the black hole down at the Eddington-limit is less than about 10^7 years and about an additional 10^8 years to reach the high prograde spin regime. Due to the fact that the gap region between the inner edge of the accretion disk and the black hole

horizon decreases in size with time, the jet power initially decreases as the spin approaches zero but then increases although never reaching its original strength at high retrograde spin. The opposite occurs for the disk power with the disk efficiency increasing as the gap region decreases in size. This behavior is shown in the first panel of Figure 3 with blue representing the fraction of the maximum jet power and red representing the fraction of the maximum disk power, both as a function of redshift. In other words, the disk power and jet power reach their maxima at different times and the y axis captures the fraction of the maximum power at a given time, allowing us to see when the system reaches its maximum luminosities in jets and disks. Here, our focus is on a narrow range in redshift in order to illustrate the basic difference in how jets and disks evolve with time. We choose to focus on the evolution of an initially high retrograde accreting black hole borne at redshift z=2 by following both its jet power and disk power as a function of redshift, by taking into account the increase in mass of the black hole associated with accretion (Moderski & Sikora 1996). By contrast, for objects that form or whose time evolution begins in the high prograde accretion regime, the disk power will not display a strong redshift evolution, as pointed out previously, due to the fact that its black hole spin cannot change beyond its maximum value. Again, the disk luminosity can change in this case only via a combination of decrease in accretion rate, as the post-merger funneling of gas onto the black hole drops, and increase in black hole mass due to accretion. The jet power in the case of a high prograde black hole is negligible since these accretion states correspond to radio quiet quasars in the gap paradigm. Given this basic understanding of the physics, we can appreciate the most glaring feature of this first panel in Figure 3, which is the difference in the peak of accretion power vs peak jet power, with the latter occurring at the earlier redshift. This fact survives in the paradigm regardless of any non-zero value assumed for the initial fraction of retrograde vs prograde black hole systems in post-mergers, due to the assumption of prolonged accretion. If we assume radiatively efficient thin disk accretion at redshift of 2, we find a difference in the

peak between jet and disk power of about Δz=.07. While jet power behaves like a damped oscillator with decrease in redshift (i.e. it drops and then increases again but not to its original value), the disk power, instead, steadily increases with decrease in redshift. In particular, the two blue and two red points near redshift of z=2 correspond to an FRII quasar jet phase. In the context of the work of Kalfontzou et al (2014), we see that if we assume that jets in such objects enhance or trigger star formation (as their observations suggest), then the model we propose naturally couples lower disk power with larger jet power. And the optical peak in these thermal disks is shifted to lower values for higher redshift. The accretion power varies by about a factor of more than 20 due to the fact that the spin is evolving from retrograde to prograde while the black hole mass increases by a factor of about 3 during that time. We avoid drawing a continuous line because we wish to impose Eddington-limited accretion only in an average sense. In other words, we do not require that the system is accreting precisely at the Eddington rate at all times, but near it, perhaps slightly above it and slightly below for periods of time that are fractions of the total 10^8 years required to spin the black hole up to maximal spin.

In Figure 3 top right panel, instead, we explore the full range in redshift by using the observed merger fraction for galaxies above 10^9 solar masses (Bertone & Conselice 2009). There are two differences here compared to the left panel. First, we are considering a family of cold gas accreting supermassive black holes as opposed to one object. Two, we are considering a larger range in redshift. Because the merger function drops as the redshift drops below a z of about 2, the total power in either jets or disks will decrease with redshift below z=2. The peak of power on this plot, therefore, represents the normalized sum over a family of radio loud and radio quiet quasars of the total jet and disk powers. Accordingly, the peak of jet power occurs at redshift of 2 on this plot due to the fact that the merger function is highest at this redshift for the most massive black holes (Bertone & Conselice 2009). And, because disk power reaches its peak at about 10^8 years after





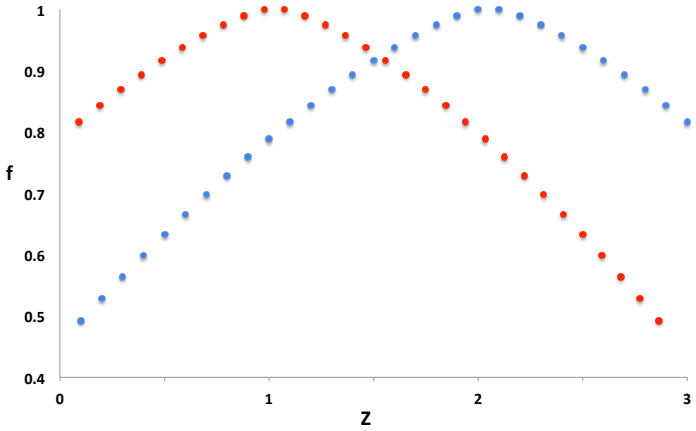


Fig. 3.— Top left: Jet and disk powers normalized to their peak values for one accreting black hole. Blue circles represent normalized jet power while red circles represent normalized disk power. The maximum disk and jet powers are both normalized to 1 for simplicity and to make it easier to see the relative peak between the two as a function of redshift. But there is no reason why the maximum disk power should equal the maximum jet power. Because the disk efficiency is lowest when the jet is most powerful, the optical peak is also lowest. Top right: The fraction of AGN that reach maximum jet power (blue) and maximum accretion power (red) normalized to the peak of such occurrences vs redshift for the most massive black holes. Using an average for the fractional merger function from Bertone & Conselice (2009), we have assumed that FRII quasars are produced in equal fractions compared to radio quiet quasars, which means that a fraction of the mergers lead to high spinning, retrograde accretion, and an equal fraction to high spinning prograde accretion. We see that the peak in jet power leads the peak in accretion power at all redshifts. Bottom: Including lower mass accreting black holes and secular processes, shifts the disk power peak to even lower redshift.

jet power, we are still capturing the same effect that appeared in the first panel, i.e. the disk power reaching its maximum at later times compared to jet power. Hence, the top panel on the right captures the evolution of the total normalized disk and jet power over a large range in redshift. We assume that mergers lead to equal fractions of high-spinning black holes in retrograde and prograde accretion, i.e. to equal fractions of radio loud and radio quiet quasars. While the radio quiet population evolves slowly, the FRII quasar class evolves quickly, turning into radio quiet quasars in less than about 10^8 years at the Eddington accretion rate. The figure includes only the most massive black holes (i.e. above 10^9 solar masses), explicitly done to highlight the differences that remain even though entire families of accreting black holes are missing. As we more realistically explore total luminosity functions by including the contribution of lower mass black holes associated with cosmic downsizing to this, as well as secular processes at lower redshift, we end up in the conditions captured by the lower panel of Figure 3. While the quantitative details depend on particular assumptions for the importance of secular processes and mergers in the lower mass black hole regime, the basic difference between the two peaks appears as a noticeable shift compared to the top right figure. Because AGN activity is shifting to lower mass accreting black holes that do not involve retrograde accretion, radio quiet quasars/AGN are beginning to dominate the energetics compared to the radio loud quasar/AGN group. From the perspective of our branching-tree diagrams, AGN activity is now dynamically dominated in a way that is captured by the second panel of Figure 1 and the first panel of Figure 2, with fewer FRII quasars forming, and secular processes becoming more dominant. We have added the contribution of massive black holes that are a factor of 10-100 times smaller than the ones that appear in Figure 3 top right panel. And, as we did for the FRII quasars and radio quiet quasars with masses above 10^9 solar masses, we use the following

expression for jet power from Garofalo, Evans & Sambruna (2010),

$$L_{jet} = 2x10^{47} ergs^{-1} \alpha\beta^2 (\frac{B_d}{10^5} G)^2 m_9^2 j^2 \quad (14)$$

where α captures the coupling between the Blandford-Znajek and Blandford-Payne processes, β prescribes the magnetic flux enhancement on the black hole due to the gap region, B_d represents the magnitude of the magnetic field threading the inner accretion disk, m_9 the black hole mass in terms of one billion solar masses, and j is the dimensionless spin parameter. Standard thin disk power, instead, is given by the integral over the entire accretion disk of the dissipation function D(R) given above. The difference with this lower black hole mass population is simply in the black hole mass, which gives smaller powers for both jets and disks. In order to capture the observational fact that secular processes begin to dominate at redshift of 1, we impose a peak in the contribution of 10^7 – 10^8 accreting solar mass black holes to disk power at about a redshift of 1. The blue function continues to drop because the majority of the objects that are forming at lower redshift are prograde accreting systems which can only produce jets when in the intermediate spin range as described in the branching-tree diagrams for cold mode accretion and these jets are less powerful compared with their retrograde cold mode accreting counterparts. Although the most massive quasars are no longer contributing to the red points at lower redshift, the large numbers of less massive accreting black holes are overwhelmingly radio quiet AGN as the redshift approaches 1 and decreases, making the overall blue peak shift considerably from that of the red peak. While the 1.05 difference in redshift between the peak in accretion and jet power should not be taken too rigorously because the uncertainties depend on rough estimates of the decrease in production of retrograde systems, on the specific fractions of lower mass accreting black holes contributing to the AGN phenomenon, as well as the details of the contribution of secular processes as a function of redshift, the

bottom line is the existence of an inescapable and noticeable break between the jet and accretion peaks in the paradigm. In other words, by working within the uncertainties in the physics we can decrease or increase the redshift difference between the two peaks but cannot wash away the existence of a shift**.** If the jet power is observed predominantly in radio, and disk power in optical/X-ray, our results are qualitatively compatible with observations (e.g. Singal et al 2013 Figure 12). This is illustrated in the bottom panel of Figure 3. Note, finally, how the red points representing the fractional disk power drop more slowly with decrease in redshift. This is due to the aforementioned fact that disk-dominated objects evolve more slowly than jet-dominated ones in the paradigm. As one decreases, and eventually completely eliminates, the contribution of lower mass black holes and secular processes from the bottom panel in Figure 3, again the difference becomes miniscule and we are back in the regime described by the top right of Figure 3. Indeed, the take away message here is that it is not the FRIIs that are responsible for the significant lag between the difference in peak between disk and jet powers. In fact, the top right of Figure 3 shows a negligible difference between those peaks. It is only when you include the effect of the AGN population as a whole that you get the large offset. However, it is important to note that although including only the most massive accreting black hole population produces a small difference, that small difference in peaks remains as a result of the fundamental distinguishing feature of the paradigm: Retrograde accretion is dynamically jet-dominated, but invariably evolves toward disk- dominated states.

In terms of the connection with star formation, thin disk efficiency is lowest for the highest retrograde spin and increases monotonically as the spin becomes more prograde (Figure 4).

At highest retrograde accretion we have the most powerful, most collimated, jets, which presumably induce star formation (Kalfountzou et al 2014). But such disks are

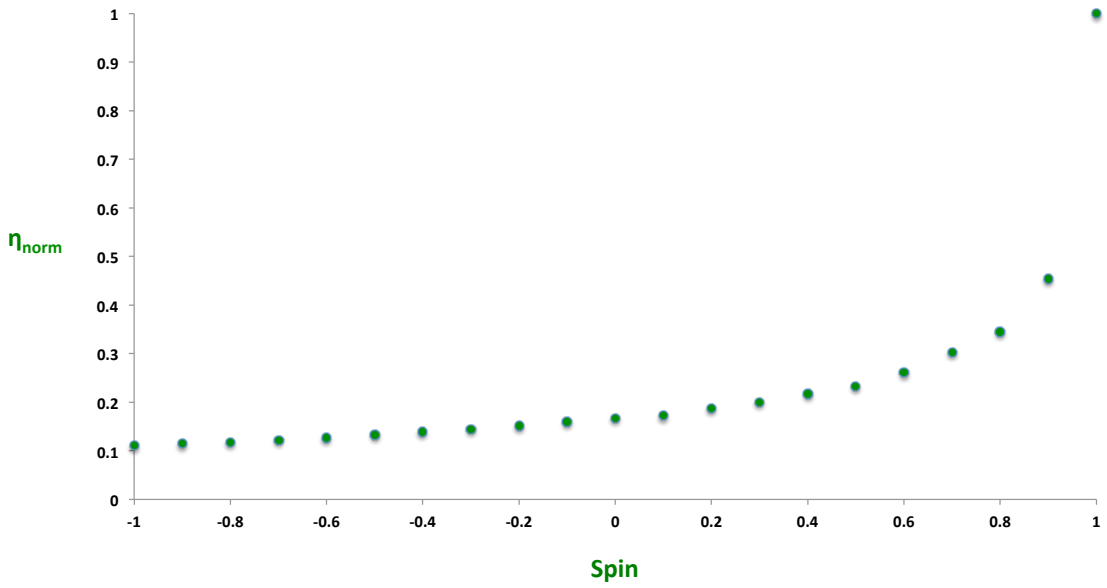


Fig. 4.— Normalized thin accretion disk efficiency. The normalized efficiency is in terms of the maximum possible efficiency which is at highest prograde spin. Because the innermost stable circular orbit is closer to the black hole as the accretion is in greater prograde regimes, the disk efficiency increases monotonically in the prograde direction up to 42% of the accreted rest mass. Negative values indicate retrograde accretion while positive values represent the prograde regime.

also the least efficient (Figure 4). At lower retrograde spins, say around -0.2 or -0.1, the accretion efficiency has increased by 1.36 to 1.43 times compared to highest retrograde spin. In addition, the black hole has accreted 10 to 15 percent of its original mass so it went from a mass M to a mass of up to 1.15M. The accretion power, therefore, increases both as a result of the change in efficiency as well as to the change in black hole mass. In order to put this on more quantitative footing, we calculate the ratio of the temperatures in the inner disks at 10 Schwarzschild radii for disks that are the result of time evolution from high retrograde spin of about -1 to a retrograde spin of -0.5. We apply standard thin disk theory and its temperature profile according to

$$T \propto r^{-3/4} M^{1/4} [1 - (r_{ISCO}/r)^{1/2}]^{1/4} \quad (15)$$

where M is the black hole mass, r_{ISCO} is the innermost stable circular orbit, and r is the radial location in the disk where we evaluate the temperature (10 Schwarschild radii). The black hole has increased its mass to about 1.1M from the initial value M and r_{ISCO} has dropped from 9 Schwarzschild radii to about 7.5 Schwarzschild radii. We find

$$T_f/T_i = 1.21 > 1 \quad (16)$$

where T_i is the temperature in the disk at 10 Schwarzschild radii when the black hole is spinning at the highest retrograde value and T_f is the temperature in the disk at 10 Schwarzschild radii when the black hole mass has increased by about 10% of its original value and the spin is -0.5. What matters to our discussion is not the actual ratio but the fact that it is larger than unity, a fact that is independent of the actual boundary value of the temperature in the inner disk. As a result of this temperature increase, the peak in the spectral intensity distribution will shift to higher energy, thereby increasing the optical luminosity. And this is true despite the fact that 10 Schwarzschild radii is further away from the event horizon when the black hole mass is larger. But this increase in the energy reprocessed in the disk is associated with an increase in disk winds (Kuncic &

Bicknell 2004, 2007) that, unlike collimated jets, may constitute negative feedback (Barger et al 2014; Kalfountzou et al 2014). To reiterate, lower optical luminosities are associated with higher retrograde accreting objects, precisely the class that in the paradigm produce the most powerful, most collimated jets, by maximizing both the Blandford-Znajek and Blandford-Payne jets (Garofalo, Evans & Sambruna 2010). As accretion spins the black hole down toward zero spin and the disk efficiency and black hole mass increase, the optical luminosity of the thin disk also increases. However, jets are becoming less powerful and less collimated due to the decreased size of the gap region (Garofalo 2009b; Garofalo, Evans & Sambruna 2010) and, therefore, are less efficient in their ability to enhance the star formation. This picture is qualitatively in agreement with the observation of Kalfountzou et al (2014) that as the optical luminosity increases (they quote a threshold value of $\log_{10}(L_{opt}/W) < 38$), the far infrared signatures of enhanced star formation disappear. And they ask what the mechanism could be that halts the positive feedback they assume the jets are having in the lower optical range. But this is expected in the gap paradigm: The optical luminosity of these accreting black holes increases as the black holes spin down from high retrograde values in tandem with the increase in black hole mass and disk efficiency. But, as noted, a lower retrograde spin implies less powerful and less collimated jets. Hence, spinning the black hole down in the retrograde regime decreases the alleged positive feedback of jets, while increasing the alleged negative feedback of disk winds. It is also important to emphasize that we are not appealing to differences in accretion rates. Everything else being equal, larger accretion rates will enhance both the jet and disk powers, which of course, have competing/opposite effects. The distinguishing element here, instead, is the disk efficiency, which depends on black hole spin. Larger disk efficiency is coupled to both less powerful and less collimated jets. It is also important to note that the jet-driven star formation we are advocating here is not simply a matter of larger jet power. At lower disk efficiency, the theory prescribes that both jet power and jet collimation,

are larger. And, as Kalfountzou et al (2014) point out, the fact that the star formation rate at higher overall power appears to remain the same as that in the lower optical regime, is compatible with the idea that while the jet-induced star formation is greater, the competing negative feedback due to stronger disk winds compensates, i.e. the disk efficiency is such that the tug-of-war between jets and disks is in balance. Overall, we come to the following explanation: Under the assumption that collimated FRII jets enhance or trigger star formation, and that un-collimated or less collimated disk winds produce negative feedback, cold mode accreting systems in high spinning retrograde configurations will *initially* enhance the star formation, but inevitably evolve toward accretion states that have the opposite effect. The conversation in terms of a tug-of-war or a competition between jets and disks described in Garofalo, Evans & Sambruna (2010), is transferrable to a conversation about the star formation connection with AGNs. Accordingly, black hole accretion borne in the far retrograde regime, will experience a shift not only in the nature of this active phase (jet dominated to disk dominated), but also in its ability to influence the host galaxy star formation by shifting the nature of its feedback (from positive to negative). It goes without saying that we have not shown that the Kalfountzou et al work cannot be interpreted in other ways. We have described how the jet-induced star formation suggested by others (Tadhunter et al 2014; Gaibler et al 2012; Crocket et al 2012; Croft et al 2006) makes sense within the gap paradigm. Very much related to the time evolution of black hole accretion used so far in this work, in the next section we include a discussion of the Soltan argument, showing how these ideas just presented allow one to also appreciate how massive, high-spinning black holes at low redshift, should be both common and radio quiet.

4. The Soltan argument: High spinning black holes and radio quiet AGN at low redshift

As emphasized in previous work (Garofalo, Evans & Sambruna 2010; Garofalo 2013a,b), high-spinning, prograde accreting black holes in radiatively efficient states, constitute the most effective conditions for the absence of jets. This disk quenching or suppression of the jet comes from observations of X-ray binaries (Ponti et al 2012; Neilsen & Lee 2009), thereby ensuring scale invariance. For post-merger, prograde, high-spin black hole accretion, jet suppression ensures such systems behave like radio quiet AGN/quasars, but for systems that begin in the retrograde regime, such jet suppression states are the product of time evolution, reached after about 10^8 years at the Eddington accretion rate. Because the model prescribes the generation of hot gas accretion as the result of a previous FRII quasar phase that was powerful enough to heat the galactic medium and affect accretion during the timescales of the accretion process (Antonuccio-Delogu & Silk 2010), most AGN will not find themselves accreting in these hot, radiatively inefficient states, and will therefore reach the high-spin black hole regime in radiatively efficient, radio quiet or jet-less states. This is captured in the branching-tree diagrams of Figures 1 and 2, with the size of the boxes representing FRI radio galaxies becoming smaller at lower redshift, and by being absent on the secular processes diagram (Figure 2). In particular, FRI radio galaxies are explicitly forbidden in the model to emerge from mergers so there are no arrows that connect the merger box to the FRI radio galaxy box. Therefore, within the paradigm, with the exception of the largest accreting black holes (whose density is in decline), decrease in redshift ensures that a large population of prograde accreting black holes must be both spinning rapidly and be associated with an absence of strong jets, ensuring compatibility with the Soltan argument. Note how cosmic downsizing implies that fewer FRII quasars will form at low redshift since FRII quasars require retrograde accretion in the paradigm which occurs only if the following conditions apply: 1) They occur statistically only in a

subset of major mergers but the merger function drops with decrease in redshift (Bertone & Conselice 2009; Treister et al 2012); 2) retrograde accretion is unstable unless the black hole is massive (Perego et al 2009; Garofalo 2013b), so less massive black holes are less likely to live long in retrograde configurations. And the observations in fact support this idea (Dunlop et al 2003; McLure & Jarvis 2004; Floyd et al 2013). This drop in the density of FRII objects as the redshift decreases is captured in Figure 1, with the smaller size of the FRII boxes. Fewer FRII quasars implies less hot halo gas-accreting FRI radio galaxies, since, as noted above and as emphasized by the arrows in the diagrams, the two are evolutionarily linked in the gap paradigm. What remains, therefore, are lower-mass accreting black holes, which precludes both the existence of retrograde and hot mode accretion, forcing accretion to exist in lower-mass black holes in prograde configurations, with the radiatively-efficient subclass of such objects being radio quiet or without jets. The non radiatively-efficient fraction, as can be seen on the diagrams, are LINERs. A bird's eye view of this suggests that compatibility with the Soltan argument is well described as the result of an evolutionary process in which accretion begins to dominate over jets, with an absence of retrograde systems and an appearance of jets only in intermediate prograde spinning black holes in radiatively efficient states. But the diagram captures the essential outcome of prolonged accretion in the paradigm: rapidly spinning, dead black holes at low redshift.

With the radio luminosity function as a proxy for jet power, and the X-ray/optical luminosity function as a proxy for accretion power, this framework is the first to make sense of a long-standing puzzle in the evolution of extragalactic radio sources, i.e. the compatibility of both the radio and X-ray/optical luminosity functions vs redshift. Within the context of the spin paradigm, in fact, high spinning prograde accreting black holes produce the most powerful jets, which observationally are detected in the radio band. But high-spinning prograde black holes have the highest disk efficiency if they are thin

disks. And they are detected in the X-ray/optical band. Hence, according to the simplest interpretation of the spin paradigm, the radio and X-ray/optical luminosity functions should track each other. The observational inference, instead, appears to be that accretion reaches its peak significantly later. Hence the spin paradigm puzzle or 'Meier paradox' (Meier 2012). We have proposed a scenario that qualitatively resolves the conflict.

5. Comparison to GRMHD

In this section we wish to address some of the confusion that has emerged over the differences between the ideas in the gap paradigm and the results of general relativistic magnetohydrodynamic numerical simulations (GRMHD), which find that prograde accreting black holes produce slightly more powerful jets than retrograde ones (e.g. Tchekhovskoy & McKinney 2012). The take away point should be that the semi-analytic foundation of the gap paradigm shares little common ground with GRMHD so that differences should be expected. The major differences between GRMHD and the gap paradigm are twofold: 1) There is an uncertainty as to what is and where the dynamo acts to produce the magnetic field and whether accretion disks predominantly advect pre-existing fields or create them in-situ (e.g. Blackman 2012 and references therein). GRMHD allows the accretion disk to act as a dynamo; hence, the closer the disk is to the black hole, the greater the field strength. By this we simply mean that GRMHD equations naturally lead to dynamo behavior while the gap paradigm forbids dynamo-like behavior in the accretion disk, hence, the first fundamental difference. And such a difference is largely responsible for determining whether retrograde or prograde black holes have larger black hole-threading fields (Garofalo 2009). And the fact that dynamo-like behavior naturally emerges from the GRMHD equations is true even in the context of the recent magnetically dominated or flooded simulations where there is an additional largescale magnetic field that is advected into the black hole region

by fiat. In fact, this largescale magnetic field will be allowed to thread the black hole or be diffused outward, depending on the field that threads the disk, via magnetic field pressures. But as field diffusion weakens the black hole threading flux, the inner disk dynamo of the prograde accreting system will enhance the magnetic field there, contributing additional magnetic pressure to hold the field on the hole. Of course this begs the question of what mechanism operates to provide the advected largescale field in the first place. While the numerical solution presented in our scheme shares the unexplained assumption of a pre-existing large-scale field, no dynamo-like behavior occurs in the accretion disk, which is thus constrained to behave as a passive advector of magnetic flux, allowing the retrograde system to experience the larger black hole threading flux due to the advectively-prone larger gap region. In other words, the no-flux boundary condition in the gap region is responsible for the differences in black hole-threading flux between the prograde and retrograde regimes. A real astrophysical black hole system likely behaves in a way that lies in-between these two extremes. 2) GRMHD adopts an ideal MHD scheme, ignoring the generalized Ohm's law. Much work has gone into showing that effective MHD parameters are produced in turbulent regimes that do not require the specification of microscopic physics (Guan & Gammie 2009; Fromang & Stone 2009; Lesur & Longaretti 2009; Eyink, Lazarian & Vishniac 2011). While there is evidence that turbulent resistivity and diffusion appear to do a good job even in relativistic regimes (Cho & Lazarian 2014), there are issues that may require non-ideal MHD, such as the generalization of the notion of flux-freezing in terms of 'magnetofluid connectivity' that may considerably alter the plasma behavior (Asenjo & Comisso 2015). These missing non-ideal terms that also ensure causality via their time dependence, may become important in the violently dynamical environment near black holes which would only be captured in the GRMHD equations if the microscopic physics were specified. In fact, current MHD work is attempting to bridge this gap in creative ways such as to change the spatial interpolation for the hydrodynamic equations and magnetodynamics equations,

thereby mimicking a change in dissipative scales (Tchekhovskoy, personal communication). While the gap paradigm includes the simplified Ohm's law, it is quite old-school in this respect, adopting the α-prescription. While two issues - the origin of magnetic fields and the nature and limitation of turbulent-driven, effective MHD in black hole plasmas – constitute a gap in our ultimate understating of strongly relativistic MHD systems that leave us with doubts in the modeling of the spin dependence of jets in both analytic and semi-analytic models like the gap paradigm as well as in numerical simulations of black hole systems, we should not be surprised that the different approaches produce different results. Ultimately, our position is that once GRMHD simulations advance beyond the idealized Ohm's law, incorporating both radiation and the required microphysics, the importance of retrograde accretion will emerge.

6. Summary and conclusion

The gap paradigm for black hole accretion and jet formation constitutes a phenomenological framework for the time evolution of AGN whose constraints from a simple prolonged accretion picture predict a specific redshift distribution for a large family of AGN. While the powerful FRII quasars are modeled as retrograde spinning systems, the implicit time evolution due to accretion ensures that their black holes spin down toward zero spin and up into the prograde regime. For the accreting systems that remain in radiatively efficient states, only for intermediate prograde black hole spins are jets allowed, as recent observations suggest in NLS1s (Doi et al, ApJ, in press; Liu et al. 2015). For high-spinning black holes in radiatively efficient accretion states, the model prescribes jet suppression, a scale-invariant mechanism whose by-products involve both jet power peak at higher redshift compared to accretion peak – qualitatively resolving the Meier Paradox - and radio quietness associated with high spinning black holes at low redshift, as we also

conclude from the Soltan argument. Our results are important because they constitute the first and only application of the model to star formation, culminating in a picture in which a subclass of the FRII quasars lead to an increase in the star formation rate resulting from the fact that large gap regions between accretion disks and black holes lead to both powerful and collimated jets as well as to thermal disks with lower peak energy, allowing jet-induced star formation to dominate over the negative feedback of disk winds. The simple time evolution of the gap paradigm has now been applied to at least qualitatively explain a host of seemingly different observations that in the model, instead, have a common explanation: the radio loud/radio quiet dichotomy, the FRI/FRII break, the difference in peak accretion power vs peak jet power vs redshift, the existence of high-spinning radio quiet AGN at low redshift, the jet-disk connection, the existence of more massive black holes in the radio loud quasar population, the reason why jets occur in intermediate prograde spinning black holes in NLS1s, the reason why disk winds are more powerful in radio quiet AGN/quasars compared to radio loud AGN/quasars, and, finally most recently to the radio quasar-star formation link. The remarkable number of observations that fit within the simple evolutionary picture of the gap paradigm argues that retrograde accretion is an essential element in our understanding of the cosmic evolution of black holes, one that numerical models capable of including the physics of the central engine in active galaxies should eventually incorporate.

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